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H., Okada, M. A., Oliver, M., Oppermann, P., Oram, Richard J., O'Reilly, B., Ormiston, R. G., Ortega, L. F., O'Shaughnessy, R., Ossokine, S., Ottaway, D. J., Overmier, H., Owen, B. J., Pace, A. E., Pagano, G., Page, M. A., Pagliaroli, G., Pai, A., Pai, S. A., Palamos, J. R., Palashov, O., Palomba, C., Pan, H., Panda, P. K., Pang, P. T. H., Pankow, C., Pannarale, F., Pant, B. C., Paoletti, F., Paoli, A., Parida, A., Parker, W., Pascucci, D., Pasqualetti, A., Passaquieti, R., Passuello, D., Patil, M., Patricelli, B., Payne, E., Pearlstone, B. L., Pechsiri, T. C., Pedersen, A. J., Pedraza, M., Pedurand, R., Pele, A., Penn, S., Perego, A., Perez, C. J., Périgois, C., Perreca, A., Petermann, J., Pfeiffer, H. P., Phelps, M., Phukon, K. S., Piccinni, O. J., Pichot, M., Piergiovanni, F., Pierro, V., Pillant, G., Pinard, L., Pinto, I. M., Pirello, M., Pitkin, M., Plastino, W., Poggiani, R., Pong, D. Y. T., Ponrathnam, S., Popolizio, P., Porter, E. K., Powell, J., Prajapati, A. K., Prasad, J., Prasai, K., Prasanna, R., Pratten, G., Prestegard, T., Principe, M., Prodi, G. A., Prokhorov, L., Punturo, M., Puppo, P., Pürner, M., Qi, Hong, Quetschke, V., Quinonez, P. J., Raab, F. J., Raaijmakers, G., Radkins, H., Radulesco, N., Raffai, P., Raja, S., Rajan, C., Rajbhandari, B., Rakhmanov, M., Ramirez, K. E., Ramos-Buades, A., Rana, Javed, Rao, K., Rapagnani, P., Raymond, Vivien ORCID: <https://orcid.org/0000-0003-0066-0095>, Razzano, M., Read, J., Regimbau, T., Rei, L., Reid, S., Reitze, D. H., Rettengo, P., Ricci, F., Richardson, C. J., Richardson, J. W., Ricker, P. M., Riemenschneider, G., Riles, K., Rizzo, M., Robertson, N. A., Robinet, F., Rocchi, A., Rolland, L., Rollins, J. G., Roma, V. J., Romanelli, M., Romano, R., Romel, C. L., Romie, J. H., Rose, C. A., Rose, D., Rose, K., Rosińska, D., Rosofsky, S. G., Ross, M. P., Rowan, S., Rüdiger, A., Ruggi, P., Rutins, G., Ryan, K., Sachdev, S., Sadecki, T., Sakellariadou, M., Salafia, O. S., Salconi, L., Saleem, M., Samajdar, A., Sammut, L., Sanchez, E. J., Sanchez, L. E., Sanchis-Gual, N., Sanders, J. R., Santiago, K. A., Santos, E., Sarin, N., Sassolas, B., Sauter, O., Savage, R. L., Schale, P., Scheel, M., Scheuer, J., Schmidt, P., Schnabel, R., Schofield, R. M. S., Schönbeck, A., Schreiber, E., Schulte, B. W., Schutz, Bernard ORCID: <https://orcid.org/0000-0001-9487-6983>, Scott, J., Scott, S. M., Seidel, E., Sellers, D., Sengupta, A. S., Sennett, N., Sentenac, D., Sequino, V., Sergeev, A., Setyawati, Y., Shaddock, D. A., Shaffer, T., Shahriar, M. S., Shaner, M. B., Sharma, A., Sharma, P., Shawhan, P., Shen, H., Shink, R., Shoemaker, D. H., Shoemaker, D. M., Shukla, K., ShyamSundar, S., Siellez, K., Sieniawska, M., Sigg, D., Singer, L. P., Singh, D., Singh, N., Singhal, A., Sintès, A. M., Sitmukhambetov, S., Skliris, Vasileios, Slagmolen, B. J. J., Slaven-Blair, T. J., Smith, J. R., Smith, R. J. E., Somala, S., Son, E. J., Soni, S., Sorazu, B., Sorrentino, F., Souradeep, T., Sowell, E., Spencer, A. P., Spera, M., Srivastava, A. K., Srivastava, V., Staats, K., Stachie, C., Standke, M., Steer, D. A., Steinke, M., Steinlechner, J., Steinlechner, S., Steinmeyer, D., Stevenson, S. P., Stocks, D., Stone, R., Stops, D. J., Strain, K. A., Stratta, G., Strigin, S. E., Strunk, A., Sturani, R., Stuver, A. L., Sudhir, V., Summerscales, T. Z., Sun, L., Sunil, S., Sur, A., Suresh, J., Sutton, Patrick ORCID: <https://orcid.org/0000-0003-1614-3922>, Swinkels, B. L., Szczepańczyk, M. J., Tacca, M., Tait, S. C., Talbot, C., Tanner, D. B., Tao, D., Tápai, M., Tapia, A., Tasson, J. D., Taylor, R., Tenorio, R., Terkowski, L., Thomas, M., Thomas, P., Thondapu, S. R., Thorne, K. A., Thrane, E., Tiwari, S., Tiwari, Srishti, Tiwari, V., Toland, K., Tonelli, M., Tornasi, Z., Torres-Forné, A., Torrie, C. I., Töyrä, D., Travasso, F., Traylor, G., Tringali, M. C., Tripathi, A., Trovato, A., Trozzo, L., Tsang, K. W., Tse, M., Tso, R., Tsukada, L., Tsuna, D., Tsutsui, T., Tuyenbayev, D., Ueno, K., Ugolini, D., Unnikrishnan, C. S., Urban, A. L., Usman, S. A., Vahlbruch, H., Vajente, G., Valdes, G., Valentini, M., Bakel, N. van, Beuzekom, M. van, Brand, J. F. J. van den, Broeck, C. Van Den, Vander-Hyde, D. C., Schaaf,

L. van der, VanHeijningen, J. V., Veggel, A. A. van, Vardaro, M., Varma, V., Vass, S., Vasúth, M., Vecchio, A., Vedovato, G., Veitch, J., Veitch, P. J., Venkateswara, K., Venugopalan, G., Verkindt, D., Vetrano, F., Viceré, A., Viets, A. D., Vinciguerra, S., Vine, D. J., Vinet, J.-Y., Vitale, S., Vo, T., Vocca, H., Vorvick, C., Vyatchanin, S. P., Wade, A. R., Wade, L. E., Wade, M., Walet, R., Walker, M., Wallace, L., Walsh, S., Wang, H., Wang, J. Z., Wang, S., Wang, W. H., Wang, Y. F., Ward, R. L., Warden, Z. A., Warner, J., Was, M., Watchi, J., Weaver, B., Wei, L.-W., Weinert, M., Weinstein, A. J., Weiss, R., Wellmann, F., Wen, L., Wessel, E. K., Weßels, P., Westhouse, J. W., Wette, K., Whelan, J. T., Whiting, B. F., Whittle, C., Wilken, D. M., Williams, D., Williamson, A. R., Willis, J. L., Willke, B., Winkler, W., Wipf, C. C., Wittel, H., Woan, G., Woehler, J., Wofford, J. K., Wright, J. L., Wu, D. S., Wysocki, D. M., Xiao, S., Xu, R., Yamamoto, H., Yancey, C. C., Yang, L., Yang, Y., Yang, Z., Yap, M. J., Yazback, M., Yeeles, David, Yu, Hang, Yu, Haocun, Yuen, S. H. R., Zadro?ny, A. K., Zadro?ny, A., Zanolin, M., Zelenova, T., Zendri, J.-P., Zevin, M., Zhang, J., Zhang, L., Zhang, T., Zhao, C., Zhao, G., Zhou, M., Zhou, Z., Zhu, X. J., Zucker, M. E., Zweizig, J. and Salemi, F. 2019. Search for eccentric binary black hole mergers with advanced LIGO and advanced Virgo during their first and second observing runs. *Astrophysical Journal* 883 (1) , 49. 10.3847/1538-4357/ab3c2d file

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Search for Eccentric Binary Black Hole Mergers with Advanced LIGO and Advanced Virgo during Their First and Second Observing Runs

B. P. Abbott¹, R. Abbott¹, T. D. Abbott², S. Abraham³, F. Acernese^{4,5}, K. Ackley⁶, C. Adams⁷, R. X. Adhikari¹, V. B. Adya⁸, C. Affeldt^{9,10}, M. Agathos^{11,12}, K. Agatsuma¹³, N. Aggarwal¹⁴, O. D. Aguiar¹⁵, L. Aiello^{16,17}, A. Ain³, P. Ajith¹⁸, G. Allen¹⁹, A. Allocca^{20,21}, M. A. Aloy²², P. A. Altin⁸, A. Amato²³, S. Anand¹, A. Ananyeva¹, S. B. Anderson¹, W. G. Anderson²⁴, S. V. Angelova²⁵, S. Antier²⁶, S. Appert¹, K. Arai¹, M. C. Araya¹, J. S. Areeda²⁷, M. Arène²⁶, N. Arnaud^{28,29}, S. M. Aronson³⁰, K. G. Arun³¹, S. Ascenzi^{16,32}, G. Ashton⁶, S. M. Aston⁷, P. Astone³³, F. Aubin³⁴, P. Aufmuth¹⁰, K. AultO'Neal³⁵, C. Austin², V. Avendano³⁶, A. Avila-Alvarez²⁷, S. Babak²⁶, P. Bacon²⁶, F. Badaracco^{16,17}, M. K. M. Bader³⁷, S. Bae³⁸, J. Baird²⁶, P. T. Baker³⁹, F. Baldaccini^{40,41}, G. Ballardini²⁹, S. W. Ballmer⁴², A. Bals³⁵, S. Banagiri⁴³, J. C. Barayoga¹, C. Barbieri^{44,45}, S. E. Barclay⁴⁶, B. C. Barish¹, D. Barker⁴⁷, K. Barkett⁴⁸, S. Barnum¹⁴, F. Barone^{5,49}, B. Barr⁴⁶, L. Barsotti¹⁴, M. Barsuglia²⁶, D. Barta⁵⁰, J. Bartlett⁴⁷, I. Bartos³⁰, R. Bassiri⁵¹, A. Basti^{20,21}, M. Bawaj^{41,52}, J. C. Bayley⁴⁶, M. Bazzan^{53,54}, B. Bécsy⁵⁵, M. Bejger^{26,56}, I. Belahcene²⁸, A. S. Bell⁵⁷, D. Beniwal⁵⁷, M. G. Benjamin³⁵, G. Bergmann^{9,10}, S. Bernuzzi¹¹, C. P. L. Berry⁵⁸, D. Bersanetti⁵⁹, A. Bertolini³⁷, J. Betzwieser⁷, R. Bhandare⁶⁰, J. Bidler²⁷, E. Biggs²⁴, I. A. Bilenko⁶¹, S. A. Bilgili³⁹, G. Billingsley¹, R. Birney²⁵, O. Birnholtz⁶², S. Biscans^{1,14}, M. Bisch^{63,64}, S. Biscoveanu¹⁴, A. Bisht¹⁰, M. Bitossi^{21,29}, M. A. Bizouard⁶⁵, J. K. Blackburn¹, J. Blackman⁴⁸, C. D. Blair⁷, D. G. Blair⁶⁶, R. M. Blair⁴⁷, S. Bloemen⁶⁷, F. Bobba^{68,69}, N. Bode^{9,10}, M. Boer⁶⁵, Y. Boetzel⁷⁰, G. Bogaert⁶⁵, F. Bondu⁷¹, R. Bonnand³⁴, P. Booker^{9,10}, B. A. Boom³⁷, R. Bork¹, V. Boschi²⁹, S. Bose³, V. Bossilkov⁶⁶, J. Bosveld⁶⁶, Y. Bouffanais^{53,54}, A. Bozzi²⁹, C. Bradaschia²¹, P. R. Brady²⁴, A. Bramley^{76,77}, M. Branchesi^{16,17}, J. E. Brau⁷², M. Breschi¹¹, T. Briant⁷³, J. H. Briggs⁴⁶, F. Brighenti^{63,64}, A. Brillet⁶⁵, M. Brinkmann^{9,10}, P. Brockill²⁴, A. F. Brooks¹, J. Brooks²⁹, D. D. Brown⁵⁷, S. Brunetti¹, A. Buikema¹⁴, T. Bulik⁷⁴, H. J. Bulten^{37,75}, A. Buonanno^{76,77}, D. Buskulic³⁴, C. Buy²⁶, R. L. Byer⁵¹, M. Cabero^{9,10}, L. Cadonati⁷⁸, G. Cagnoli⁷⁹, C. Cahillane¹, J. Calderón Bustillo⁶, T. A. Callister¹, E. Calloni^{5,80}, J. B. Camp⁸¹, W. A. Campbell⁶, M. Canepa^{59,82}, K. C. Cannon⁸³, H. Cao⁵⁷, J. Cao⁸⁴, G. Carapella^{68,69}, F. Carbognani²⁹, S. Caride⁸⁵, M. F. Carney⁵⁸, G. Carullo^{20,21}, J. Casanueva Diaz²¹, C. Casentini^{32,86}, S. Caudill³⁷, M. Cavaglia^{87,88}, F. Cavalier²⁸, R. Cavalieri²⁹, G. Cella²¹, P. Cerdá-Durán²², E. Cesarini^{32,89}, O. Chaibi⁶⁵, K. Chakravarti³, S. J. Chamberlin⁹⁰, M. Chan⁴⁶, S. Chao⁹¹, P. Charlton⁹², E. A. Chase⁵⁸, E. Chassande-Mottin²⁶, D. Chatterjee²⁴, M. Chaturvedi⁶⁰, B. D. Cheeseboro³⁹, H. Y. Chen⁹³, X. Chen⁶⁶, Y. Chen⁴⁸, H.-P. Cheng³⁰, C. K. Cheong⁹⁴, H. Y. Chia³⁰, F. Chiadini^{69,95}, A. Chincarini⁵⁹, A. Chiummo²⁹, G. Cho⁹⁶, H. S. Cho⁹⁷, M. Cho⁷⁷, N. Christensen^{65,98}, Q. Chu⁶⁶, S. Chua⁷³, K. W. Chung⁹⁴, S. Chung⁶⁶, G. Ciani^{53,54}, M. Cieřlar⁵⁶, A. A. Ciobanu⁵⁷, R. Ciolfi^{54,99}, F. Cipriano⁶⁵, A. Cirone^{59,82}, F. Clara⁴⁷, J. A. Clark⁷⁸, P. Clearwater¹⁰⁰, F. Cleva⁶⁵, E. Coccia^{16,17}, P.-F. Cohadon⁷³, D. Cohen²⁸, M. Colleoni¹⁰¹, C. G. Collette¹⁰², C. Collins¹³, M. Colpi^{44,45}, L. R. Cominsky¹⁰³, M. Constanicio Jr.¹⁵, L. Conti⁵⁴, S. J. Cooper¹³, P. Corban⁷, T. R. Corbitt², I. Cordero-Carrión¹⁰⁴, S. Corezzi^{40,41}, K. R. Corley¹⁰⁵, N. Cornish⁵⁵, D. Corre²⁸, A. Corsi⁸⁵, S. Cortese²⁹, C. A. Costa¹⁵, R. Cotesta⁷⁶, M. W. Coughlin¹, S. B. Coughlin^{58,106}, J.-P. Coulon⁶⁵, S. T. Countryman¹⁰⁵, P. Couvares¹, P. B. Covas¹⁰¹, E. E. Cowan⁷⁸, D. M. Coward⁶⁶, M. J. Cowart⁷, D. C. Coyne¹, R. Coyne¹⁰⁷, J. D. E. Creighton²⁴, T. D. Creighton¹⁰⁸, J. Cripe², M. Croquette⁷³, S. G. Crowder¹⁰⁹, T. J. Cullen², A. Cumming⁴⁶, L. Cunningham⁴⁶, E. Cuoco²⁹, T. Dal Canton⁸¹, G. Dálya¹¹⁰, B. D'Angelo^{59,82}, S. L. Danilishin^{9,10}, S. D'Antonio³², K. Danzmann^{9,10}, A. Dasgupta¹¹¹, C. F. Da Silva Costa³⁰, L. E. H. Dattier⁴⁶, V. Dattilo²⁹, I. Dave⁶⁰, M. Davies²⁸, D. Davis⁴², E. J. Daw¹¹², D. DeBra⁵¹, M. Deenadayalan³, J. Degallaix²³, M. De Laurentis^{5,80}, S. Deléglise⁷³, W. Del Pozzo^{20,21}, L. M. DeMarchi⁵⁸, N. Demos¹⁴, T. Dent¹¹³, R. De Pietri^{114,115}, R. De Rosa^{5,80}, C. De Rossi^{23,29}, G. DeSalvo¹¹⁶, O. de Varona^{9,10}, S. Dhurandhar³, M. C. Díaz¹⁰⁸, T. Dietrich³⁷, L. Di Fiore⁵, C. DiFronzo¹³, C. Di Giorgio^{68,69}, F. Di Giovanni²², M. Di Giovanni^{117,118}, T. Di Girolamo^{5,80}, A. Di Lieto^{20,21}, B. Ding¹⁰², S. Di Pace^{33,119}, I. Di Palma^{33,119}, F. Di Renzo^{20,21}, A. K. Divakarla³⁰, A. Dmitriev¹³, Z. Doctor⁹³, F. Donovan¹⁴, K. L. Dooley^{87,106}, S. Doravari³, I. Dorrington¹⁰⁶, T. P. Downes²⁴, M. Drago^{16,17}, J. C. Driggers⁴⁷, Z. Du⁸⁴, J.-G. Ducoin²⁸, P. Dupej⁴⁶, O. Durante^{68,69}, S. E. Dwyer⁴⁷, P. J. Easter⁶, G. Eddolls⁴⁶, T. B. Edo¹¹², A. Effler⁷, P. Ehrens¹, J. Eichholz⁸, S. S. Eikenberry³⁰, M. Eisenmann³⁴, R. A. Eisenstein¹⁴, L. Errico^{5,80}, R. C. Essick⁹³, H. Estelles¹⁰¹, D. Estevez³⁴, Z. B. Etienne³⁹, T. Etzel¹, M. Evans¹⁴, T. M. Evans⁷, V. Fafone^{16,32,86}, S. Fairhurst¹⁰⁶, X. Fan⁸⁴, S. Farinon⁵⁹, B. Farr⁷², W. M. Farr¹³, E. J. Fauchon-Jones¹⁰⁶, M. Favata³⁶, M. Fays¹¹², M. Fazio¹²⁰, C. Fee¹²¹, J. Feicht¹, M. M. Fejer⁵¹, F. Feng²⁶, A. Fernandez-Galiana¹⁴, I. Ferrante^{20,21}, E. C. Ferreira¹⁵, T. A. Ferreira¹⁵, F. Fidecaro^{20,21}, I. Fiori²⁹, D. Fiorucci^{16,17}, M. Fishbach⁹³, R. P. Fisher¹²², J. M. Fishner¹⁴, R. Fittipaldi^{69,123}, M. Fitz-Axen⁴³, V. Fiumara^{69,124}, R. Flaminio^{34,125}, M. Fletcher⁴⁶, E. Floden⁴³, E. Flynn²⁷, H. Fong⁸³, J. A. Font^{22,126}, P. W. F. Forsyth⁸, J.-D. Fournier⁶⁵, Francisco Hernandez Vivanco⁶, S. Frasca^{33,119}, F. Frasconi²¹, Z. Frei¹¹⁰, A. Freise¹³, R. Frey⁷², V. Frey²⁸, P. Fritschel¹⁴, V. V. Frolov⁷, G. Fronze¹²⁷, P. Fulda³⁰, M. Fyffe⁷, H. A. Gabbard⁴⁶, B. U. Gadre⁷⁶, S. M. Gaebel¹³, J. R. Gair¹²⁸, L. Gammaitoni⁴⁰, S. G. Gaonkar³, C. García-Quirós¹⁰¹, F. Garuffi^{5,80}, B. Gateley⁴⁷, S. Gaudio³⁵, G. Gaur¹²⁹, V. Gayathri¹³⁰, G. Gemme⁵⁹, E. Genin²⁹, A. Gennai²¹, D. George¹⁹, J. George⁶⁰, L. Gergely¹³¹, S. Ghonge⁷⁸, Abhirup Ghosh⁷⁶, Archisman Ghosh³⁷, S. Ghosh²⁴, B. Giacomazzo^{117,118}, J. A. Giaime^{2,7}, K. D. Giardina⁷, D. R. Gibson¹³², K. Gill¹⁰⁵, L. Glover¹³³, J. Griesmer¹³⁴, P. Godwin⁹⁰, E. Goetz⁴⁷, R. Goetz³⁰, B. Goncharov⁶, G. González², J. M. Gonzalez Castro^{20,21}, A. Gopakumar¹³⁵, S. E. Gossan¹, M. Gosselin^{20,21,29}, R. Gouaty³⁴, B. Grace⁸, A. Grado^{5,136}, M. Granata²³, A. Grant⁴⁶, S. Gras¹⁴, P. Grassia¹, C. Gray⁴⁷, R. Gray⁴⁶, G. Greco^{63,64}, A. C. Green³⁰, R. Green¹⁰⁶, E. M. Gretarsson³⁵, A. Grimaldi^{117,118}, S. J. Grimm^{16,17}, P. Groot⁶⁷, H. Grote¹⁰⁶

S. Grunewald⁷⁶, P. Gruning²⁸, G. M. Guidi^{63,64}, H. K. Gulati¹¹¹, Y. Guo³⁷, A. Gupta⁹⁰, Anchal Gupta¹, P. Gupta³⁷, E. K. Gustafson¹, R. Gustafson¹³⁷, L. Haegel¹⁰¹, O. Halim^{16,17}, B. R. Hall¹³⁸, E. D. Hall¹⁴, E. Z. Hamilton¹⁰⁶, G. Hammond⁴⁶, M. Haney⁷⁰, M. M. Hanke^{9,10}, J. Hanks⁴⁷, C. Hanna⁹⁰, M. D. Hannam¹⁰⁶, O. A. Hannuksela⁹⁴, T. J. Hansen³⁵, J. Hanson⁷, T. Harder⁶⁵, T. Hardwick², K. Haris¹⁸, J. Harms^{16,17}, G. M. Harry¹³⁹, I. W. Harry¹⁴⁰, R. K. Hasskew⁷, C. J. Haster¹⁴, K. Haughian⁴⁶, F. J. Hayes⁴⁶, J. Healy⁶², A. Heidmann⁷³, M. C. Heintze⁷, H. Heitmann⁶⁵, F. Hellman¹⁴¹, P. Hello²⁸, G. Hemming²⁹, M. Hendry⁴⁶, I. S. Heng⁴⁶, J. Hennig^{9,10}, M. Heurs^{9,10}, S. Hild⁴⁶, T. Hinderer^{37,142,143}, S. Hochheim^{9,10}, D. Hofman²³, A. M. Holgado¹⁹, N. A. Holland⁸, K. Holt⁷, D. E. Holz⁹³, P. Hopkins¹⁰⁶, C. Horst²⁴, J. Hough⁴⁶, E. J. Howell⁶⁶, C. G. Hoy¹⁰⁶, Y. Huang¹⁴, M. T. Hübner⁶, E. A. Huerta¹⁹, D. Huet²⁸, B. Hughey³⁵, V. Hui³⁴, S. Husa¹⁰¹, S. H. Huttner⁴⁶, T. Huynh-Dinh⁷, B. Idzkowski⁷⁴, A. Iess^{32,86}, H. Inchauspe³⁰, C. Ingram⁵⁷, R. Inta⁸⁵, G. Intini^{33,119}, B. Irwin¹²¹, H. N. Isa⁴⁶, J.-M. Isac⁷³, M. Isi¹⁴, B. R. Iyer¹⁸, T. Jacqmin⁷³, S. J. Jadhav¹⁴⁴, K. Jani⁷⁸, N. N. Janthalur¹⁴⁴, P. Jaranowski¹⁴⁵, D. Jariwala³⁰, A. C. Jenkins¹⁴⁶, J. Jiang³⁰, D. S. Johnson¹⁹, A. W. Jones¹³, D. I. Jones¹⁴⁷, J. D. Jones⁴⁷, R. Jones⁴⁶, R. J. G. Jonker³⁷, L. Ju⁶⁶, J. Junker^{9,10}, C. V. Kalaghatgi¹⁰⁶, V. Kalogera⁵⁸, B. Kamai¹, S. Kandhasamy³, G. Kang³⁸, J. B. Kanner¹, S. J. Kapadia²⁴, S. Karki⁷², R. Kashyap¹⁸, M. Kasprzak¹, S. Katsanevas²⁹, E. Katsavounidis¹⁴, W. Katzman⁷, S. Kaufer¹⁰, K. Kawabe⁴⁷, N. V. Keerthana³, F. Kéfélian⁶⁵, D. Keitel¹⁴⁰, R. Kennedy¹¹², J. S. Key¹⁴⁸, F. Y. Khalili⁶¹, I. Khan^{16,32}, S. Khan^{9,10}, E. A. Khazanov¹⁴⁹, N. Khetan^{16,17}, M. Khursheed⁶⁰, N. Kijbunchoo⁸, Chunglee Kim¹⁵⁰, J. C. Kim¹⁵¹, K. Kim⁹⁴, W. Kim⁵⁷, W. S. Kim¹⁵², Y.-M. Kim¹⁵³, C. Kimball⁵⁸, P. J. King⁴⁷, M. Kinley-Hanlon⁴⁶, R. Kirchhoff^{9,10}, J. S. Kissel⁴⁷, L. Kleybolte¹³⁴, J. H. Klika²⁴, S. Klimenko³⁰, T. D. Knowles³⁹, P. Koch^{9,10}, S. M. Koehlenbeck^{9,10}, G. Koekoek^{37,154}, S. Koley³⁷, V. Kondrashov¹, A. Kontos¹⁵⁵, N. Koper^{9,10}, M. Korobko¹³⁴, W. Z. Korth¹, M. Kovalam⁶⁶, D. B. Kozak¹, C. Krämer^{9,10}, V. Kringel^{9,10}, N. Krishnendu³¹, A. Królak^{156,157}, N. Krupinski²⁴, G. Kuehn^{9,10}, A. Kumar¹⁴⁴, P. Kumar¹⁵⁸, Rahul Kumar⁴⁷, Rakesh Kumar¹¹¹, L. Kuo⁹¹, A. Kutynia¹⁵⁶, S. Kwang²⁴, B. D. Lackey⁷⁶, D. Laghi^{20,21}, K. H. Lai⁹⁴, T. L. Lam⁹⁴, M. Landry⁴⁷, B. B. Lane¹⁴, R. N. Lang¹⁵⁹, J. Lange⁶², B. Lantz⁵¹, R. K. Lanza¹⁴, A. Lartaux-Vollard²⁸, P. D. Lasky⁶, M. Laxen⁷, A. Lazzarini¹, C. Lazzaro⁵⁴, P. Leaci^{33,119}, S. Leavey^{9,10}, Y. K. Lecoecue⁴⁷, C. H. Lee⁹⁷, H. K. Lee¹⁶⁰, H. M. Lee¹⁶¹, H. W. Lee¹⁵¹, J. Lee⁹⁶, K. Lee⁴⁶, J. Lehmann^{9,10}, A. K. Lenon³⁹, N. Leroy²⁸, N. Letendre³⁴, Y. Levin⁶, A. Li⁹⁴, J. Li⁸⁴, K. J. L. Li⁹⁴, T. G. F. Li⁹⁴, X. Li⁴⁸, F. Lin⁶, F. Linde^{37,162}, S. D. Linker¹³³, T. B. Littenberg¹⁶³, J. Liu⁶⁶, X. Liu²⁴, M. Llorens-Monteagudo²², R. K. L. Lo¹⁹⁴, L. T. London¹⁴, A. Longo^{164,165}, M. Lorenzini^{16,17}, V. Lorette¹⁶⁶, M. Lormand⁷, G. Losurdo²¹, J. D. Lough^{9,10}, C. O. Lousto⁶², G. Lovelace²⁷, M. E. Lower¹⁶⁷, H. Lück^{9,10}, D. Lumaca^{32,86}, A. P. Lundgren¹⁴⁰, R. Lynch¹⁴, Y. Ma⁴⁸, R. Macas¹⁰⁶, S. Macfoy²⁵, M. MacInnis¹⁴, D. M. Macleod¹⁰⁶, A. Macquet⁶⁵, I. Magaña Hernandez²⁴, F. Magaña-Sandoval³⁰, R. M. Magee⁹⁰, E. Majorana³³, I. Maksimovic¹⁶⁶, A. Malik⁶⁰, N. Man⁶⁵, V. Mandic⁴³, V. Mangano^{33,46,119}, G. L. Mansell^{14,47}, M. Manske²⁴, M. Mantovani²⁹, M. Mapelli^{53,54}, F. Marchesoni^{41,52}, F. Marion³⁴, S. Márka¹⁰⁵, Z. Márka¹⁰⁵, C. Markakis¹⁹, A. S. Markosyan⁵¹, A. Markowitz¹, E. Maros¹, A. Marquina¹⁰⁴, S. Marsat²⁶, F. Martelli^{63,64}, I. W. Martin⁴⁶, R. M. Martin³⁶, V. Martinez⁷⁹, D. V. Martynov¹³, H. Masalehdan¹³⁴, K. Mason¹⁴, E. Massera¹¹², A. Masserot³⁴, T. J. Massinger¹, M. Masso-Reid⁴⁶, S. Mastrogiovanni²⁶, A. Matas⁷⁶, F. Matichard^{1,14}, L. Matone¹⁰⁵, N. Mavalvala¹⁴, J. J. McCann⁶⁶, R. McCarthy⁴⁷, D. E. McClelland⁸, S. McCormick⁷, L. McCuller¹⁴, S. C. McGuire¹⁶⁸, C. McIsaac¹⁴⁰, J. McIver¹, D. J. McManus⁸, T. McRae⁸, S. T. McWilliams³⁹, D. Meacher²⁴, G. D. Meadors⁶, M. Mehmet^{9,10}, A. K. Mehta¹⁸, J. Meidam³⁷, E. Mejuto Villa^{69,116}, A. Melatos¹⁰⁰, G. Mendell⁴⁷, R. A. Mercer²⁴, L. Mereni²³, K. Merfeld⁷², E. L. Merilh⁴⁷, M. Merzougui⁶⁵, S. Meshkov¹, C. Messenger⁴⁶, C. Messick⁹⁰, F. Messina^{44,45}, R. Metzdrorf⁷³, P. M. Meyers¹⁰⁰, F. Meylahn^{9,10}, A. Miani^{117,118}, H. Miao¹³, C. Michel²³, H. Middleton¹⁰⁰, L. Milano^{5,80}, A. L. Miller^{30,33,119}, M. Millhouse¹⁰⁰, J. C. Mills¹⁰⁶, M. C. Milovich-Goff¹³³, O. Minazzoli^{65,169}, Y. Minenkov³², A. Mishkin³⁰, C. Mishra¹⁷⁰, T. Mistry¹¹², S. Mitra³, V. P. Mitrofanov⁶¹, G. Mitselmakher³⁰, R. Mittleman¹⁴, G. Mo⁹⁸, D. Moffa¹²¹, K. Mogushi⁸⁷, S. R. P. Mohapatra¹⁴, M. Molina-Ruiz¹⁴¹, M. Mondin¹³³, M. Montani^{63,64}, C. J. Moore¹³, D. Moraru⁴⁷, F. Morawski⁵⁶, G. Moreno⁴⁷, S. Morisaki⁸³, B. Mours³⁴, C. M. Mow-Lowry¹³, F. Muciaccia^{33,119}, Arunava Mukherjee^{9,10}, D. Mukherjee²⁴, S. Mukherjee¹⁰⁸, Subroto Mukherjee¹¹¹, N. Mukund^{3,9,10}, A. Mullavey⁷, J. Munch⁵⁷, E. A. Muñoz⁴², M. Muratore³⁵, P. G. Murray⁴⁶, I. Nardecchia^{32,86}, L. Naticchioni^{33,119}, R. K. Nayak¹⁷¹, B. F. Neil⁶⁶, J. Neilson^{69,116}, G. Nelemans^{37,67}, T. J. N. Nelson⁷, M. Nery^{9,10}, A. Neunzert¹³⁷, L. Nevin¹, K. Y. Ng¹⁴, S. Ng⁵⁷, C. Nguyen²⁶, P. Nguyen⁷², D. Nichols^{37,142}, S. A. Nichols², S. Nissanke^{37,142}, F. Nocera²⁹, C. North¹⁰⁶, L. K. Nuttall¹⁴⁰, M. Obergaulinger^{22,172}, J. Oberling⁴⁷, B. D. O'Brien³⁰, G. Oganessian^{16,17}, G. H. Ogin¹⁷³, J. J. Oh¹⁵², S. H. Oh¹⁵², F. Ohme^{9,10}, H. Ohta⁸³, M. A. Okada¹⁵, M. Oliver¹⁰¹, P. Oppermann^{9,10}, Richard J. Oram⁷, B. O'Reilly⁷, R. G. Ormiston⁴³, L. F. Ortega³⁰, R. O'Shaughnessy⁶², S. Ossokine⁷⁶, D. J. Ottaway⁵⁷, H. Overmire⁷, B. J. Owen⁸⁵, A. E. Pace⁹⁰, G. Pagano^{20,21}, M. A. Page⁶⁶, G. Pagliaroli^{16,17}, A. Pai¹³⁰, S. A. Pai⁶⁰, J. R. Palamos⁷², O. Palashov¹⁴⁹, C. Palomba³³, H. Pan⁹¹, P. K. Panda¹⁴⁴, P. T. H. Pang^{37,94}, C. Pankow⁵⁸, F. Pannarale^{33,119}, B. C. Pant⁶⁰, F. Paoletti²¹, A. Paoli²⁹, A. Parida³, W. Parker^{7,168}, D. Pascucci^{37,46}, A. Pasqualetti²⁹, R. Passaquietti^{20,21}, D. Passuello²¹, M. Patil¹⁵⁷, B. Patricelli^{20,21}, E. Payne⁶, B. L. Pearlstone⁴⁶, T. C. Pechsiri³⁰, A. J. Pedersen⁴², M. Pedraza¹, R. Pedurand^{23,174}, A. Pele⁷, S. Penn¹⁷⁵, A. Perego^{117,118}, C. J. Perez⁴⁷, C. Périgois³⁴, A. Perreca^{117,118}, J. Petermann¹³⁴, H. P. Pfeiffer⁷⁶, M. Phelps^{9,10}, K. S. Phukon³, O. J. Piccinni^{33,119}, M. Pichot⁶⁵, F. Piergiovanni^{63,64}, V. Pierro^{69,116}, G. Pillant²⁹, L. Pinard²³, I. M. Pinto^{69,89,116}, M. Pirello⁴⁷, M. Pitkin⁴⁶, W. Plastino^{164,165}, R. Poggiani^{20,21}, D. Y. T. Pong⁹⁴, S. Ponrathnam³, P. Popolizio²⁹, E. K. Porter²⁶, J. Powell¹⁶⁷, A. K. Prajapati¹¹¹, J. Prasad³, K. Prasai⁵¹, R. Prasanna¹⁴⁴, G. Pratten¹⁰¹, T. Prestegard²⁴, M. Principe^{69,89,116}, G. A. Prodi^{117,118}, L. Prokhorov¹³, M. Punturo⁴¹, P. Puppo³³, M. Pürer⁷⁶, H. Qi¹⁰⁶, V. Quetschke¹⁰⁸, P. J. Quinonez³⁵, F. J. Raab⁴⁷, G. Raaijmakers^{37,142}, H. Radkins⁴⁷, N. Radulesco⁶⁵, P. Raffai¹¹⁰, S. Raja⁶⁰, C. Rajan⁶⁰, B. Rajbhandari⁸⁵, M. Rakhmanov¹⁰⁸, K. E. Ramirez¹⁰⁸, A. Ramos-Buades¹⁰¹, Javed Rana³, K. Rao⁵⁸, P. Rapagnani^{33,119}, V. Raymond¹⁰⁶

M. Razzano^{20,21}, J. Read²⁷, T. Regimbau³⁴, L. Rei⁵⁹, S. Reid²⁵, D. H. Reitze^{1,30}, P. Rettigno^{127,176}, F. Ricci^{33,119}, C. J. Richardson³⁵, J. W. Richardson¹, P. M. Ricker¹⁹, G. Riemenschneider^{127,176}, K. Riles¹³⁷, M. Rizzo⁵⁸, N. A. Robertson^{1,46}, F. Robinet²⁸, A. Rocchi³², L. Rolland³⁴, J. G. Rollins¹, V. J. Roma⁷², M. Romanelli⁷¹, R. Romano^{4,5}, C. L. Romel⁴⁷, J. H. Romie⁷, C. A. Rose²⁴, D. Rose²⁷, K. Rose¹²¹, D. Rosińska⁷⁴, S. G. Rosofsky¹⁹, M. P. Ross¹⁷⁷, S. Rowan⁴⁶, A. Rüdiger^{9,10,192}, P. Ruggeri²⁹, G. Rutins¹³², K. Ryan⁴⁷, S. Sachdev⁹⁰, T. Sadecki⁴⁷, M. Sakellariadou¹⁴⁶, O. S. Salafia^{44,45,178}, L. Salconi²⁹, M. Saleem³¹, A. Samajdar³⁷, L. Sammut⁶, E. J. Sanchez¹, L. E. Sanchez¹, N. Sanchis-Gual¹⁷⁹, J. R. Sanders¹⁸⁰, K. A. Santiago³⁶, E. Santos⁶⁵, N. Sarin⁶, B. Sassolas²³, O. Sauter^{34,137}, R. L. Savage⁴⁷, P. Schale⁷², M. Scheel⁴⁸, J. Scheuer⁵⁸, P. Schmidt^{13,67}, R. Schnabel¹³⁴, R. M. S. Schofield⁷², A. Schönbeck¹³⁴, E. Schreiber^{9,10}, B. W. Schulte^{9,10}, B. F. Schutz¹⁰⁶, J. Scott⁴⁶, S. M. Scott⁸, E. Seidel¹⁹, D. Sellers⁷, A. S. Sengupta¹⁸¹, N. Sennett⁷⁶, D. Sentenac²⁹, V. Sequino⁵⁹, A. Sergeev¹⁴⁹, Y. Setyawati^{9,10}, D. A. Shaddock⁸, T. Shaffer⁴⁷, M. S. Shahriar⁵⁸, M. B. Shaner¹³³, A. Sharma^{16,17}, P. Sharma⁶⁰, P. Shawhan⁷⁷, H. Shen¹⁹, R. Shink¹⁸², D. H. Shoemaker¹⁴, D. M. Shoemaker⁷⁸, K. Shukla¹⁴¹, S. ShyamSundar⁶⁰, K. Siellez⁷⁸, M. Sieniawska⁵⁶, D. Sigg⁴⁷, L. P. Singer⁸¹, D. Singh⁹⁰, N. Singh⁷⁴, A. Singhal^{16,33}, A. M. Sintes¹⁰¹, S. Sitmukhambetov¹⁰⁸, V. Skliris¹⁰⁶, B. J. J. Slagmolen⁸, T. J. Slaven-Blair⁶⁶, J. R. Smith²⁷, R. J. E. Smith⁶, S. Somala¹⁸³, E. J. Son¹⁵², S. Soni², B. Sorazu⁴⁶, F. Sorrentino⁵⁹, T. Souradeep³, E. Sowell⁸⁵, A. P. Spencer⁴⁶, M. Spera^{53,54}, A. K. Srivastava¹¹¹, V. Srivastava⁴², K. Staats⁵⁸, C. Stachie⁶⁵, M. Standke^{9,10}, D. A. Steer²⁶, M. Steinke^{9,10}, J. Steinlechner^{46,134}, S. Steinlechner¹³⁴, D. Steinmeyer^{9,10}, S. P. Stevenson¹⁶⁷, D. Stocks⁵¹, R. Stone¹⁰⁸, D. J. Stops¹³, K. A. Strain⁴⁶, G. Stratta^{64,184}, S. E. Strigin⁶¹, A. Strunk⁴⁷, R. Sturani¹⁸⁵, A. L. Stuver¹⁸⁶, V. Sudhir¹⁴, T. Z. Summerscales¹⁸⁷, L. Sun¹, S. Sunil¹¹¹, A. Sur⁵⁶, J. Suresh⁸³, P. J. Sutton¹⁰⁶, B. L. Swinkels³⁷, M. J. Szczepańczyk³⁵, M. Tacca³⁷, S. C. Tait⁴⁶, C. Talbot⁶, D. B. Tanner³⁰, D. Tao¹, M. Tápai¹³¹, A. Tapia²⁷, J. D. Tasson⁹⁸, R. Taylor¹, R. Tenorio¹⁰¹, L. Terkowski¹³⁴, M. Thomas⁷, P. Thomas⁴⁷, S. R. Thondapu⁶⁰, K. A. Thorne⁷, E. Thrane⁶, Shubhanshu Tiwari^{117,118}, Srishti Tiwari¹³⁵, V. Tiwari¹⁰⁶, K. Toland⁴⁶, M. Tonelli^{20,21}, Z. Tornasi⁴⁶, A. Torres-Forné¹⁸⁸, C. I. Torrie¹, D. Töyrä¹³, F. Travasso^{29,41}, G. Traylor⁷, M. C. Tringali⁷⁴, A. Tripathi¹³⁷, A. Trovato²⁶, L. Trozzo^{21,189}, K. W. Tsang³⁷, M. Tse¹⁴, R. Tso⁴⁸, L. Tsukada⁸³, D. Tsuna⁸³, T. Tsutsui⁸³, D. Tuyenbayev¹⁰⁸, K. Ueno⁸³, D. Ugolini¹⁹⁰, C. S. Unnikrishnan¹³⁵, A. L. Urban², S. A. Usman⁹³, H. Vahlbruch¹⁰, G. Vajente¹, G. Valdes², M. Valentini^{117,118}, N. van Bakel³⁷, M. van Beuzekom³⁷, J. F. J. van den Brand^{37,75}, C. Van Den Broeck^{37,191}, D. C. Vander-Hyde⁴², L. van der Schaaf³⁷, J. V. VanHeijningen⁶⁶, A. A. van Veggel⁴⁶, M. Vardaro^{53,54}, V. Varma⁴⁸, S. Vass¹, M. Vasúth⁵⁰, A. Vecchio¹³, G. Vedovato⁵⁴, J. Veitch⁴⁶, P. J. Veitch⁵⁷, K. Venkateswara¹⁷⁷, G. Venugopalan¹, D. Verkindt³⁴, F. Vetrano^{63,64}, A. Vicere^{63,64}, A. D. Viets²⁴, S. Vinciguerra¹³, D. J. Vine¹³², J.-Y. Vinet⁶⁵, S. Vitale¹⁴, T. Vo⁴², H. Vocca^{40,41}, C. Vorvick⁴⁷, S. P. Vyatchanin⁶¹, A. R. Wade¹, L. E. Wade¹²¹, M. Wade¹²¹, R. Walet³⁷, M. Walker²⁷, L. Wallace¹, S. Walsh²⁴, H. Wang¹³, J. Z. Wang¹³⁷, S. Wang¹⁹, W. H. Wang¹⁰⁸, Y. F. Wang⁹⁴, R. L. Ward⁸, Z. A. Warden³⁵, J. Warner⁴⁷, M. Was³⁴, J. Watchi¹⁰², B. Weaver⁴⁷, L.-W. Wei^{9,10}, M. Weinert^{9,10}, A. J. Weinstein¹, R. Weiss¹⁴, F. Wellmann^{9,10}, L. Wen⁶⁶, E. K. Wessel¹⁹, P. Weßels^{9,10}, J. W. Westhouse³⁵, K. Wette⁸, J. T. Whelan⁶², B. F. Whiting³⁰, C. Whittle¹⁴, D. M. Wilken^{9,10}, D. Williams⁴⁶, A. R. Williamson^{37,142}, J. L. Willis¹, B. Willke^{9,10}, W. Winkler^{9,10}, C. C. Wipf¹, H. Wittel^{9,10}, G. Woan⁴⁶, J. Woehler^{9,10}, J. K. Wofford⁶², J. L. Wright⁴⁶, D. S. Wu^{9,10}, D. M. Wysocki⁶², S. Xiao¹, R. Xu¹⁰⁹, H. Yamamoto¹, C. C. Yancey⁷⁷, L. Yang¹²⁰, Y. Yang³⁰, Z. Yang⁴³, M. J. Yap⁸, M. Yazback³⁰, D. W. Yeeles¹⁰⁶, Hang Yu¹⁴, Haocun Yu¹⁴, S. H. R. Yuen⁹⁴, A. K. Zadrożny¹⁰⁸, A. Zadrożny¹⁵⁶, M. Zanolin³⁵, T. Zelenova²⁹, J.-P. Zendri⁵⁴, M. Zevin⁵⁸, J. Zhang⁶⁶, L. Zhang¹, T. Zhang⁴⁶, C. Zhao⁶⁶, G. Zhao¹⁰², M. Zhou⁵⁸, Z. Zhou⁵⁸, X. J. Zhu⁶, M. E. Zucker^{1,14}, J. Zweigig¹

(The LIGO Scientific Collaboration and the Virgo Collaboration), and

F. Salemi⁹

¹ LIGO, California Institute of Technology, Pasadena, CA 91125, USA

² Louisiana State University, Baton Rouge, LA 70803, USA

³ Inter-University Centre for Astronomy and Astrophysics, Pune 411007, India

⁴ Dipartimento di Farmacia, Università di Salerno, I-84084 Fisciano, Salerno, Italy

⁵ INFN, Sezione di Napoli, Complesso Universitario di Monte S. Angelo, I-80126 Napoli, Italy

⁶ OzGrav, School of Physics & Astronomy, Monash University, Clayton 3800, Victoria, Australia

⁷ LIGO Livingston Observatory, Livingston, LA 70754, USA

⁸ OzGrav, Australian National University, Canberra, Australian Capital Territory 0200, Australia

⁹ Max Planck Institute for Gravitational Physics (Albert Einstein Institute), D-30167 Hannover, Germany

¹⁰ Leibniz Universität Hannover, D-30167 Hannover, Germany

¹¹ Theoretisch-Physikalisches Institut, Friedrich-Schiller-Universität Jena, D-07743 Jena, Germany

¹² University of Cambridge, Cambridge CB2 1TN, UK

¹³ University of Birmingham, Birmingham B15 2TT, UK

¹⁴ LIGO, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

¹⁵ Instituto Nacional de Pesquisas Espaciais, 12227-010 São José dos Campos, São Paulo, Brazil

¹⁶ Gran Sasso Science Institute (GSSI), I-67100 L'Aquila, Italy

¹⁷ INFN, Laboratori Nazionali del Gran Sasso, I-67100 Assergi, Italy

¹⁸ International Centre for Theoretical Sciences, Tata Institute of Fundamental Research, Bengaluru 560089, India

¹⁹ NCSA, University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA

²⁰ Università di Pisa, I-56127 Pisa, Italy

²¹ INFN, Sezione di Pisa, I-56127 Pisa, Italy

²² Departament de Astronomia i Astrofísica, Universitat de València, E-46100 Burjassot, València, Spain

²³ Laboratoire des Matériaux Avancés (LMA), CNRS/IN2P3, F-69622 Villeurbanne, France

²⁴ University of Wisconsin-Milwaukee, Milwaukee, WI 53201, USA

²⁵ SUPA, University of Strathclyde, Glasgow G1 1XQ, UK

- ²⁶ APC, AstroParticule et Cosmologie, Université Paris Diderot, CNRS/IN2P3, CEA/Irfu, Observatoire de Paris, Sorbonne Paris Cité, F-75205 Paris Cedex 13, France
- ²⁷ California State University Fullerton, Fullerton, CA 92831, USA
- ²⁸ LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, F-91898 Orsay, France
- ²⁹ European Gravitational Observatory (EGO), I-56021 Cascina, Pisa, Italy
- ³⁰ University of Florida, Gainesville, FL 32611, USA
- ³¹ Chennai Mathematical Institute, Chennai 603103, India
- ³² INFN, Sezione di Roma Tor Vergata, I-00133 Roma, Italy
- ³³ INFN, Sezione di Roma, I-00185 Roma, Italy
- ³⁴ Laboratoire d'Annecy de Physique des Particules (LAPP), Univ. Grenoble Alpes, Université Savoie Mont Blanc, CNRS/IN2P3, F-74941 Annecy, France
- ³⁵ Embry-Riddle Aeronautical University, Prescott, AZ 86301, USA
- ³⁶ Montclair State University, Montclair, NJ 07043, USA
- ³⁷ Nikhef, Science Park 105, 1098 XG Amsterdam, The Netherlands
- ³⁸ Korea Institute of Science and Technology Information, Daejeon 34141, Republic of Korea
- ³⁹ West Virginia University, Morgantown, WV 26506, USA
- ⁴⁰ Università di Perugia, I-06123 Perugia, Italy
- ⁴¹ INFN, Sezione di Perugia, I-06123 Perugia, Italy
- ⁴² Syracuse University, Syracuse, NY 13244, USA
- ⁴³ University of Minnesota, Minneapolis, MN 55455, USA
- ⁴⁴ Università degli Studi di Milano-Bicocca, I-20126 Milano, Italy
- ⁴⁵ INFN, Sezione di Milano-Bicocca, I-20126 Milano, Italy
- ⁴⁶ SUPA, University of Glasgow, Glasgow G12 8QQ, UK
- ⁴⁷ LIGO Hanford Observatory, Richland, WA 99352, USA
- ⁴⁸ Caltech CaRT, Pasadena, CA 91125, USA
- ⁴⁹ Dipartimento di Medicina, Chirurgia e Odontoiatria "Scuola Medica Salernitana," Università di Salerno, I-84081 Baronissi, Salerno, Italy
- ⁵⁰ Wigner RCP, RMKI, H-1121 Budapest, Konkoly Thege Miklós út 29-33, Hungary
- ⁵¹ Stanford University, Stanford, CA 94305, USA
- ⁵² Università di Camerino, Dipartimento di Fisica, I-62032 Camerino, Italy
- ⁵³ Università di Padova, Dipartimento di Fisica e Astronomia, I-35131 Padova, Italy
- ⁵⁴ INFN, Sezione di Padova, I-35131 Padova, Italy
- ⁵⁵ Montana State University, Bozeman, MT 59717, USA
- ⁵⁶ Nicolaus Copernicus Astronomical Center, Polish Academy of Sciences, 00-716, Warsaw, Poland
- ⁵⁷ OzGrav, University of Adelaide, Adelaide, South Australia 5005, Australia
- ⁵⁸ Center for Interdisciplinary Exploration & Research in Astrophysics (CIERA), Northwestern University, Evanston, IL 60208, USA
- ⁵⁹ INFN, Sezione di Genova, I-16146 Genova, Italy
- ⁶⁰ RRCAT, Indore, Madhya Pradesh 452013, India
- ⁶¹ Faculty of Physics, Lomonosov Moscow State University, Moscow 119991, Russia
- ⁶² Rochester Institute of Technology, Rochester, NY 14623, USA
- ⁶³ Università degli Studi di Urbino "Carlo Bo," I-61029 Urbino, Italy
- ⁶⁴ INFN, Sezione di Firenze, I-50019 Sesto Fiorentino, Firenze, Italy
- ⁶⁵ Artemis, Université Côte d'Azur, Observatoire Côte d'Azur, CNRS, CS 34229, F-06304 Nice Cedex 4, France
- ⁶⁶ OzGrav, University of Western Australia, Crawley, Western Australia 6009, Australia
- ⁶⁷ Department of Astrophysics/IMAPP, Radboud University Nijmegen, P.O. Box 9010, 6500 GL Nijmegen, The Netherlands
- ⁶⁸ Dipartimento di Fisica "E.R. Caianiello," Università di Salerno, I-84084 Fisciano, Salerno, Italy
- ⁶⁹ INFN, Sezione di Napoli, Gruppo Collegato di Salerno, Complesso Universitario di Monte S. Angelo, I-80126 Napoli, Italy
- ⁷⁰ Physik-Institut, University of Zurich, Winterthurerstrasse 190, 8057 Zurich, Switzerland
- ⁷¹ Univ Rennes, CNRS, Institut FOTON—UMR6082, F-3500 Rennes, France
- ⁷² University of Oregon, Eugene, OR 97403, USA
- ⁷³ Laboratoire Kastler Brossel, Sorbonne Université, CNRS, ENS-Université PSL, Collège de France, F-75005 Paris, France
- ⁷⁴ Astronomical Observatory Warsaw University, 00-478 Warsaw, Poland
- ⁷⁵ VU University Amsterdam, 1081 HV Amsterdam, The Netherlands
- ⁷⁶ Max Planck Institute for Gravitational Physics (Albert Einstein Institute), D-14476 Potsdam-Golm, Germany
- ⁷⁷ University of Maryland, College Park, MD 20742, USA
- ⁷⁸ School of Physics, Georgia Institute of Technology, Atlanta, GA 30332, USA
- ⁷⁹ Université de Lyon, Université Claude Bernard Lyon 1, CNRS, Institut Lumière Matière, F-69622 Villeurbanne, France
- ⁸⁰ Università di Napoli "Federico II," Complesso Universitario di Monte S. Angelo, I-80126 Napoli, Italy
- ⁸¹ NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA
- ⁸² Dipartimento di Fisica, Università degli Studi di Genova, I-16146 Genova, Italy
- ⁸³ RESCEU, University of Tokyo, Tokyo, 113-0033, Japan
- ⁸⁴ Tsinghua University, Beijing 100084, People's Republic of China
- ⁸⁵ Texas Tech University, Lubbock, TX 79409, USA
- ⁸⁶ Università di Roma Tor Vergata, I-00133 Roma, Italy
- ⁸⁷ The University of Mississippi, University, MS 38677, USA
- ⁸⁸ Missouri University of Science and Technology, Rolla, MO 65409, USA
- ⁸⁹ Museo Storico della Fisica e Centro Studi e Ricerche "Enrico Fermi," I-00184 Roma, Italy
- ⁹⁰ The Pennsylvania State University, University Park, PA 16802, USA
- ⁹¹ National Tsing Hua University, Hsinchu City, 30013 Taiwan, Republic of People's Republic of China
- ⁹² Charles Sturt University, Wagga Wagga, New South Wales 2678, Australia
- ⁹³ University of Chicago, Chicago, IL 60637, USA
- ⁹⁴ The Chinese University of Hong Kong, Shatin, NT, Hong Kong
- ⁹⁵ Dipartimento di Ingegneria Industriale (DIIN), Università di Salerno, I-84084 Fisciano, Salerno, Italy
- ⁹⁶ Seoul National University, Seoul 08826, Republic of Korea
- ⁹⁷ Pusan National University, Busan 46241, Republic of Korea
- ⁹⁸ Carleton College, Northfield, MN 55057, USA
- ⁹⁹ INAF, Osservatorio Astronomico di Padova, I-35122 Padova, Italy
- ¹⁰⁰ OzGrav, University of Melbourne, Parkville, Victoria 3010, Australia

- ¹⁰¹ Universitat de les Illes Balears, IAC3—IIEC, E-07122 Palma de Mallorca, Spain
- ¹⁰² Université Libre de Bruxelles, Brussels B-1050, Belgium
- ¹⁰³ Sonoma State University, Rohnert Park, CA 94928, USA
- ¹⁰⁴ Departamento de Matemáticas, Universitat de València, E-46100 Burjassot, València, Spain
- ¹⁰⁵ Columbia University, New York, NY 10027, USA
- ¹⁰⁶ Cardiff University, Cardiff CF24 3AA, UK
- ¹⁰⁷ University of Rhode Island, Kingston, RI 02881, USA
- ¹⁰⁸ The University of Texas Rio Grande Valley, Brownsville, TX 78520, USA
- ¹⁰⁹ Bellevue College, Bellevue, WA 98007, USA
- ¹¹⁰ MTA-ELTE Astrophysics Research Group, Institute of Physics, Eötvös University, Budapest 1117, Hungary
- ¹¹¹ Institute for Plasma Research, Bhat, Gandhinagar 382428, India
- ¹¹² The University of Sheffield, Sheffield S10 2TN, UK
- ¹¹³ IGFAE, Campus Sur, Universidade de Santiago de Compostela, E-15782 Spain
- ¹¹⁴ Dipartimento di Scienze Matematiche, Fisiche e Informatiche, Università di Parma, I-43124 Parma, Italy
- ¹¹⁵ INFN, Sezione di Milano Bicocca, Gruppo Collegato di Parma, I-43124 Parma, Italy
- ¹¹⁶ Dipartimento di Ingegneria, Università del Sannio, I-82100 Benevento, Italy
- ¹¹⁷ Università di Trento, Dipartimento di Fisica, I-38123 Povo, Trento, Italy
- ¹¹⁸ INFN, Trento Institute for Fundamental Physics and Applications, I-38123 Povo, Trento, Italy
- ¹¹⁹ Università di Roma “La Sapienza,” I-00185 Roma, Italy
- ¹²⁰ Colorado State University, Fort Collins, CO 80523, USA
- ¹²¹ Kenyon College, Gambier, OH 43022, USA
- ¹²² Christopher Newport University, Newport News, VA 23606, USA
- ¹²³ CNR-SPIN, c/o Università di Salerno, I-84084 Fisciano, Salerno, Italy
- ¹²⁴ Scuola di Ingegneria, Università della Basilicata, I-85100 Potenza, Italy
- ¹²⁵ National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan
- ¹²⁶ Observatori Astronòmic, Universitat de València, E-46980 Paterna, València, Spain
- ¹²⁷ INFN Sezione di Torino, I-10125 Torino, Italy
- ¹²⁸ School of Mathematics, University of Edinburgh, Edinburgh EH9 3FD, UK
- ¹²⁹ Institute Of Advanced Research, Gandhinagar 382426, India
- ¹³⁰ Indian Institute of Technology Bombay, Powai, Mumbai 400 076, India
- ¹³¹ University of Szeged, Dóm tér 9, Szeged 6720, Hungary
- ¹³² SUPA, University of the West of Scotland, Paisley PA1 2BE, UK
- ¹³³ California State University, Los Angeles, 5151 State University Dr, Los Angeles, CA 90032, USA
- ¹³⁴ Universität Hamburg, D-22761 Hamburg, Germany
- ¹³⁵ Tata Institute of Fundamental Research, Mumbai 400005, India
- ¹³⁶ INAF, Osservatorio Astronomico di Capodimonte, I-80131 Napoli, Italy
- ¹³⁷ University of Michigan, Ann Arbor, MI 48109, USA
- ¹³⁸ Washington State University, Pullman, WA 99164, USA
- ¹³⁹ American University, Washington, D.C. 20016, USA
- ¹⁴⁰ University of Portsmouth, Portsmouth, PO1 3FX, UK
- ¹⁴¹ University of California, Berkeley, CA 94720, USA
- ¹⁴² GRAPPA, Anton Pannekoek Institute for Astronomy and Institute for High-Energy Physics, University of Amsterdam, Science Park 904, 1098 XH Amsterdam, The Netherlands
- ¹⁴³ Delta Institute for Theoretical Physics, Science Park 904, 1090 GL Amsterdam, The Netherlands
- ¹⁴⁴ Directorate of Construction, Services & Estate Management, Mumbai 400094 India
- ¹⁴⁵ University of Białystok, 15-424 Białystok, Poland
- ¹⁴⁶ King’s College London, University of London, London WC2R 2LS, UK
- ¹⁴⁷ University of Southampton, Southampton SO17 1BJ, UK
- ¹⁴⁸ University of Washington Bothell, Bothell, WA 98011, USA
- ¹⁴⁹ Institute of Applied Physics, Nizhny Novgorod, 603950, Russia
- ¹⁵⁰ Ewha Womans University, Seoul 03760, Republic of Korea
- ¹⁵¹ Inje University Gimhae, South Gyeongsang 50834, Republic of Korea
- ¹⁵² National Institute for Mathematical Sciences, Daejeon 34047, Republic of Korea
- ¹⁵³ Ulsan National Institute of Science and Technology, Ulsan 44919, Republic of Korea
- ¹⁵⁴ Maastricht University, P.O. Box 616, 6200 MD Maastricht, The Netherlands
- ¹⁵⁵ Bard College, 30 Campus Rd, Annandale-On-Hudson, NY 12504, USA
- ¹⁵⁶ NCBJ, 05-400 Świerk-Otwock, Poland
- ¹⁵⁷ Institute of Mathematics, Polish Academy of Sciences, 00656 Warsaw, Poland
- ¹⁵⁸ Cornell University, Ithaca, NY 14850, USA
- ¹⁵⁹ Hillsdale College, Hillsdale, MI 49242, USA
- ¹⁶⁰ Hanyang University, Seoul 04763, Republic of Korea
- ¹⁶¹ Korea Astronomy and Space Science Institute, Daejeon 34055, Republic of Korea
- ¹⁶² Institute for High-Energy Physics, University of Amsterdam, Science Park 904, 1098 XH Amsterdam, The Netherlands
- ¹⁶³ NASA Marshall Space Flight Center, Huntsville, AL 35811, USA
- ¹⁶⁴ Dipartimento di Matematica e Fisica, Università degli Studi Roma Tre, I-00146 Roma, Italy
- ¹⁶⁵ INFN, Sezione di Roma Tre, I-00146 Roma, Italy
- ¹⁶⁶ ESPCI, CNRS, F-75005 Paris, France
- ¹⁶⁷ OzGrav, Swinburne University of Technology, Hawthorn VIC 3122, Australia
- ¹⁶⁸ Southern University and A&M College, Baton Rouge, LA 70813, USA
- ¹⁶⁹ Centre Scientifique de Monaco, 8 quai Antoine 1er, MC-98000, Monaco
- ¹⁷⁰ Indian Institute of Technology Madras, Chennai 600036, India
- ¹⁷¹ IISER-Kolkata, Mohanpur, West Bengal 741252, India
- ¹⁷² Institut für Kernphysik, Theoriezentrum, D-64289 Darmstadt, Germany
- ¹⁷³ Whitman College, 345 Boyer Avenue, Walla Walla, WA 99362 USA
- ¹⁷⁴ Université de Lyon, F-69361 Lyon, France
- ¹⁷⁵ Hobart and William Smith Colleges, Geneva, NY 14456, USA

- ¹⁷⁶ Dipartimento di Fisica, Università degli Studi di Torino, I-10125 Torino, Italy
¹⁷⁷ University of Washington, Seattle, WA 98195, USA
¹⁷⁸ INAF, Osservatorio Astronomico di Brera sede di Merate, I-23807 Merate, Lecco, Italy
¹⁷⁹ Centro de Astrofísica e Gravitação (CENTRA), Departamento de Física, Instituto Superior Técnico, Universidade de Lisboa, 1049-001 Lisboa, Portugal
¹⁸⁰ Marquette University, 11420 W. Clybourn St., Milwaukee, WI 53233, USA
¹⁸¹ Indian Institute of Technology, Gandhinagar Ahmedabad Gujarat 382424, India
¹⁸² Université de Montréal/Polytechnique, Montreal, Quebec H3T 1J4, Canada
¹⁸³ Indian Institute of Technology Hyderabad, Sangareddy, Khandi, Telangana 502285, India
¹⁸⁴ INAF, Osservatorio di Astrofisica e Scienza dello Spazio, I-40129 Bologna, Italy
¹⁸⁵ International Institute of Physics, Universidade Federal do Rio Grande do Norte, Natal RN 59078-970, Brazil
¹⁸⁶ Villanova University, 800 Lancaster Ave, Villanova, PA 19085, USA
¹⁸⁷ Andrews University, Berrien Springs, MI 49104, USA
¹⁸⁸ Max Planck Institute for Gravitationalphysik (Albert Einstein Institute), D-14476 Potsdam-Golm, Germany
¹⁸⁹ Università di Siena, I-53100 Siena, Italy
¹⁹⁰ Trinity University, San Antonio, TX 78212, USA
¹⁹¹ Van Swinderen Institute for Particle Physics and Gravity, University of Groningen, Nijenborgh 4, 9747 AG Groningen, The Netherlands
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Abstract

When formed through dynamical interactions, stellar-mass binary black holes (BBHs) may retain eccentric orbits ($e > 0.1$ at 10 Hz) detectable by ground-based gravitational-wave detectors. Eccentricity can therefore be used to differentiate dynamically formed binaries from isolated BBH mergers. Current template-based gravitational-wave searches do not use waveform models associated with eccentric orbits, rendering the search less efficient for eccentric binary systems. Here we present the results of a search for BBH mergers that inspiral in eccentric orbits using data from the first and second observing runs (O1 and O2) of Advanced LIGO and Advanced Virgo. We carried out the search with the coherent WaveBurst algorithm, which uses minimal assumptions on the signal morphology and does not rely on binary waveform templates. We show that it is sensitive to binary mergers with a detection range that is weakly dependent on eccentricity for all bound systems. Our search did not identify any new binary merger candidates. We interpret these results in light of eccentric binary formation models. We rule out formation channels with rates $\gtrsim 100 \text{ Gpc}^{-3} \text{ yr}^{-1}$ for $e > 0.1$, assuming a black hole mass spectrum with a power-law index $\lesssim 2$.

Unified Astronomy Thesaurus concepts: [Gravitational waves \(678\)](#); [Elliptical orbits \(457\)](#); [Astrophysical black holes \(98\)](#)

1. Introduction

In their first two observing runs, the Advanced LIGO and Advanced Virgo detectors discovered 10 binary black hole (BBH) mergers and a binary neutron star merger (Abbott et al. 2019e). These detections have already provided a wealth of information on cosmic processes, including the rate, mass, spin, and redshift distribution of BBH mergers (Abbott et al. 2016f, 2019d), constraints on general relativity (Abbott et al. 2016e, 2019c), estimates of the Hubble constant (Abbott et al. 2017a, 2019b; Soares-Santos et al. 2019), and constraints on multi-messenger emission from the mergers (Abbott et al. 2008, 2016d, 2019a; Adrián-Martínez et al. 2016; Albert et al. 2017; Burns et al. 2019).

A key question that remains unanswered is how BBHs are formed. Viable formation channels include isolated binary evolution (e.g., Bethe & Brown 1998; Belczynski et al. 2002, 2014, 2016; Dominik et al. 2013; Mennekens & Vanbeveren 2014; Spera et al. 2015; Eldridge & Stanway 2016; Mandel & de Mink 2016; Marchant et al. 2016; Mapelli et al. 2017; Stevenson et al. 2017; Barrett et al. 2018; Giacobbo & Mapelli 2018; Kruckow et al. 2018; Mapelli & Giacobbo 2018) and dynamical encounters in dense stellar environments, such as globular clusters (e.g., Portegies Zwart & McMillan 2000;

O’Leary et al. 2006; Sadowski et al. 2008; Downing et al. 2010, 2011; Rodriguez et al. 2015, 2016a, 2016b; Askar et al. 2017; Fragione & Kocsis 2018; Rodriguez & Loeb 2018; Samsing 2018; Samsing et al. 2018; Zevin et al. 2019), young star clusters (e.g., Banerjee et al. 2010; Ziosi et al. 2014; Mapelli 2016; Banerjee 2017, 2018; Di Carlo et al. 2019; Kumamoto et al. 2019), and galactic nuclei (e.g., O’Leary et al. 2009; Antonini & Perets 2012; Antonini & Rasio 2016; Petrovich & Antonini 2017; Stone et al. 2017a, 2017b; Rasskazov & Kocsis 2019). Moreover, the dynamical process known as Kozai–Lidov (KL) resonance (Kozai 1962; Lidov 1962) can trigger the merger of a BBH, even if the BBH has not been formed in a dense star cluster. In fact, if the BBH is orbited by a tertiary body (i.e., the BBH is the inner binary of a stable hierarchical triple system), the KL mechanism triggers oscillations of the BBH’s eccentricity, which might speed up the merger by gravitational-wave emission. Each channel is expected to produce black hole mergers with different mass and spin distributions (Mandel & O’Shaughnessy 2010; Abbott et al. 2016a; Rodriguez et al. 2016c; Farr et al. 2017; Abbott et al. 2019d). The limited statistics from the low number of systems detected through gravitational waves and model uncertainties so far do not allow strong constraints on the formation channels.

Orbital eccentricity is a distinguishing feature of dynamical formation channels. Gravitational-wave emission acts to circularize binary orbits by the time they reach the orbital frequencies to which Advanced LIGO and Advanced Virgo are sensitive ($\gtrsim 10$ Hz). Eccentric orbits in the Advanced LIGO and Advanced Virgo band indicate either that the binary was

¹⁹² Deceased, 2018 July.



formed with small orbital separation and therefore did not have time to circularize, or that some dynamical process increased the eccentricity. For example, KL-induced mergers are expected to be associated with high eccentricities (Antonini et al. 2017; Fragione & Bromberg 2019; Fragione & Kocsis 2019; Fragione et al. 2019a). The detection of gravitational waves from an eccentric binary would suggest that binary systems can form dynamically, and could help distinguish between different dynamical formation scenarios (KL oscillations in triple systems or dynamical encounters in dense stellar clusters; Lower et al. 2018).

In the following we define eccentricity at the time when the gravitational-wave frequency of the binary is at 10 Hz (Peters & Mathews 1963). Eccentricity constantly evolves during the inspiral.

Template-based gravitational-wave searches used by Advanced LIGO and Advanced Virgo currently do not include eccentric orbital templates (Abbott et al. 2019e). Quasicircular waveform templates are able to detect binaries with small eccentricities ($e \lesssim 0.1$), but are inefficient at extracting moderately to highly eccentric binaries (Brown & Zimmerman 2010). Multiple efforts for generating the full inspiral-merger ringdown waveforms for the binaries with eccentric orbits are underway (Cao & Han 2017; Hinderer & Babak 2017; Hinder et al. 2018; Huerta et al. 2018; Ireland et al. 2019). However, the lack of a reliable and complete waveform model prevents the implementation of a matched-filtering search at this time, and led to the development of alternative search methods (Coughlin et al. 2015; Tiwari et al. 2016; Lower et al. 2018).

Here we report the results of a search for eccentric BBH mergers with the coherent WaveBurst (cWB) algorithm that does not rely on binary system waveforms. cWB is sensitive to binaries of any eccentricity, and in particular to high-mass black holes. The search has been carried out over data from Advanced LIGO and Advanced Virgo’s O1 and O2 observing runs, and found no evidence of eccentric binary signals. This paper evaluates the sensitivity of cWB to eccentric binary mergers, and infers constraints from non-detection on the rate of eccentric mergers.

2. Detectors and Analysis Method

2.1. Advanced LIGO and Advanced Virgo

The Advanced LIGO detectors began their first observing run O1 on 2015 September 12, which lasted until 2016 January 19 (Abbott et al. 2016b). During this time they accumulated $T_{\text{obs},1} = 48$ days of coincident data during which both the LIGO Hanford and LIGO Livingston detectors were operating. The second observing run O2 started on 2016 November 30 and lasted until 2017 August 25, resulting in $T_{\text{obs},2} = 118$ days of coincident data (Abbott et al. 2019e). Advanced Virgo joined the Advanced LIGO detectors on 2017 August 1. The detectors’ sensitivity was not uniform during these runs, and there was a marked sensitivity increase from O1 to O2 (Abbott et al. 2018). As adding Advanced Virgo data was not improving the sensitivity of the search, this analysis only uses data from the Advanced LIGO detectors.

2.2. Search Description

The search for eccentric BBH mergers uses the same configuration of the cWB pipeline (Klimenko et al. 2008, 2016)

as the BBH merger search reported in Abbott et al. (2019e). An early version of the search is described in Tiwari et al. (2016). cWB is designed to search for transient signals, without specifying a waveform model. It identifies coherent excess power in multi-resolution time-frequency representations of the detectors’ strain data, for signal frequencies up to 1 kHz and duration up to a few seconds. The excess power is collected in the time-frequency plane assuming monotonically increasing frequency for better collection of the signal energy from BBHs. The search identifies events that are coherent in multiple detectors and reconstructs the source sky location and signal waveforms using the constrained maximum likelihood method.

The cWB detection statistic ρ is based on the coherent energy E_c obtained by cross-correlating the signal waveforms reconstructed in the network of detectors. It is proportional to the coherent network signal-to-noise ratio. The estimation of statistical significance of an event is done by ranking the ρ of the event against the ρ distribution for background events obtained by repeating the analysis on time-shifted data. To exclude astrophysical events from the background sample, the time shifts are much larger than the expected signal delay between the detectors. Each cWB event was assigned a False Alarm Rate based on the rate of background triggers with a ρ higher than that of the event.

To increase the robustness against non-stationary detector noise-generating glitches, cWB uses signal-independent vetoes: the network correlation $c_c = E_c/(E_c + E_n)$, where E_n is the residual noise energy estimated after the reconstructed signal pixels are subtracted from the data. For a gravitational-wave signal we expected $c_c \approx 1$, while for glitches $c_c \ll 1$. Events with $c_c < 0.7$ are rejected.

Detector characterization studies are also carried out to ensure that candidate events are not due to instrumental or environmental artifacts. We have rejected the times where significant instrumental artifacts make the data unusable (Abbott et al. 2016c).

2.3. Simulated Astrophysical Signals

In order to estimate the sensitivity of our search, we simulated eccentric BBH signals, injected them into detector data and searched for them using cWB. We used a BH mass range of $5 M_\odot$ – $50 M_\odot$ (Abbott et al. 2019d), and eccentricities in the $e \in [0, 0.99]$ range. We assumed that BHs have zero spin. These simulations were carried out to quantify the search sensitivity for individual binaries. Below we considered different mass distributions to characterize our sensitivity.

At the time of the analysis only one set of templates was available for the generation of full inspiral-merger-ringdown eccentric binary waveforms, including generic spin configurations by East et al. (2013). It uses a prescription based on the equations of motion of a geodesic in a Kerr spacetime, coupled with the quadrupole formula for the gravitational radiation. The model defines an effective Kerr spacetime whose mass and spin parameters are set equal to the total mass and orbital angular momentum of the binary. The binary is evolved based on the behavior of a timelike geodesic in the effective Kerr spacetime, but the mass and angular momentum of this spacetime are changed at each time step based on the emitted energy and angular momentum calculated in the quadrupole approximation. This approach reproduces the correct orbital dynamics in the Newtonian limit and general-relativistic test particle limit. This model also incorporates strong-field features such as

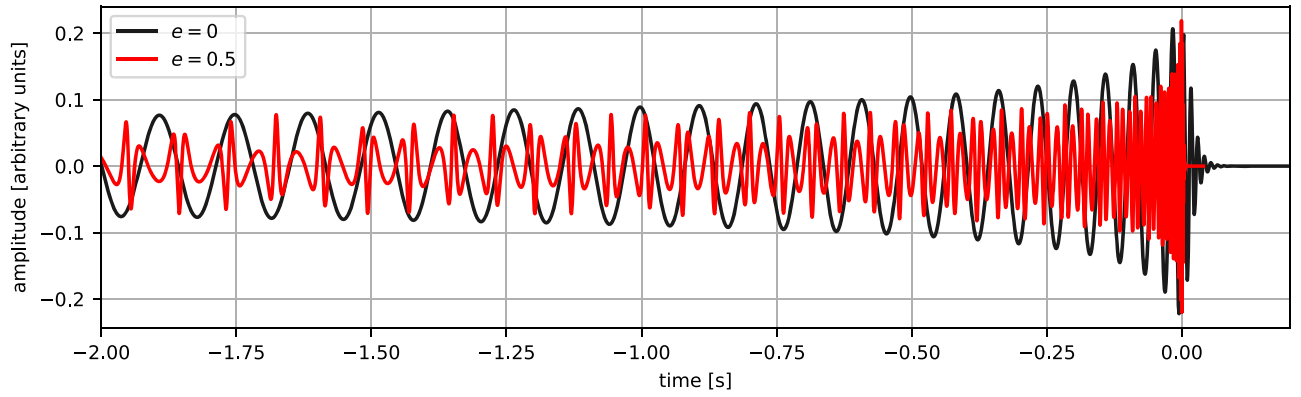


Figure 1. Examples of gravitational waveforms for a $10 M_{\odot}$ – $10 M_{\odot}$ BBH system with eccentricities 0 (black) and 0.5 (red).

pericenter precession, frame dragging, and the existence of unstable orbits and related zoom-whirl dynamics (East et al. 2013). The inspiral waveforms obtained using the above treatment are stitched to a merger model that was developed for quasicircular mergers but also performs well for eccentric mergers with little modification (Baker et al. 2008; Kelly et al. 2011). In Figure 1 we show this waveform for the case of circular and eccentric ($e = 0.5$) orbits.

The waveforms we used here to simulate gravitational waves from eccentric binaries are approximate. Compared to gravitational waveforms obtained using general-relativistic numerical simulations, the waveforms differ in overlap by up to a few percent (East et al. 2013). However, we found that cWB can detect the waveforms used here with equal sensitivity to precise waveforms obtained using numerical simulations, making their use appropriate to characterize search sensitivity. This is due to the fact that cWB does not rely on the precise gravitational waveform, making a few percent difference negligible.

3. Results

This search has detected 7 of the 10 BBH events that were identified by template-based searches (its sensitivity compared to template-based searches is higher for higher-mass binaries; see Table 1 in Abbott et al. 2019e). We considered these events to have no eccentricity. Our search did not detect any gravitational-wave event beyond these. Therefore, we concluded that no eccentric BBH merger has been detected. Below we present our search sensitivity to interpret this non-detection.

We note that the detection of only 7 out of 10 BBH events by cWB is consistent with its relative sensitivity compared to template-based searches, which are more sensitive in particular at low black hole masses (see Figure 2). Our interpretation below does not depend on or make use of this fractional overlap between the two search types.

We further note that the detection by cWB and the less-confident template-based detection of an event would not necessarily mean that the event was an eccentric binary (see, e.g., Abbott et al. 2019e). The eccentricity of a detected event would need to be independently measured (e.g., Lower et al. 2018).

3.1. Sensitivity to Eccentric Mergers

We characterized the sensitivity of our search by calculating its *range*—the distance, averaged over observation time, sky location, and orientation, within which a BBH can be detected with false alarm rate $\leq 10^{-2} \text{ yr}^{-1}$. For this calculation we

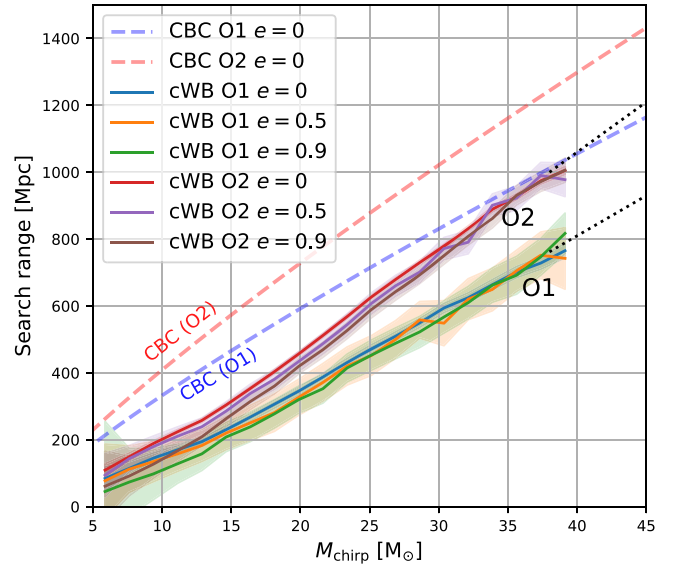


Figure 2. Range of the cWB analysis to BBH mergers as a function of the binary's chirp mass, separately for the O1 and O2 observing runs, and for different orbital eccentricities (see the legend). The shaded regions represent 1σ uncertainties. The dotted lines are linear fits on the ranges at chirp masses $> 30 M_{\odot}$ for $e = 0$. For comparison, we show the sensitive ranges for template-based searches for compact binary coalescence (CBC), assuming $e = 0$, for O1 and O2 (Abbott et al. 2018). Masses are given in source frame.

adopted a standard cosmological model with Hubble parameter $H_0 = 67.9 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $\Omega_M = 0.3065$ (Ade et al. 2016). The range depends on the black hole masses, and is different for the O1 and O2 observing runs. In particular it depends on the chirp mass \mathcal{M} of the binary, where $\mathcal{M} \equiv (m_1 m_2)^{3/5} (m_1 + m_2)^{-1/5}$ for black hole masses m_1 and m_2 . We find that cWB range is independent of the eccentricity for the whole mass range considered (see also Tiwari et al. 2016). Our ranges, using the eccentric waveforms described in Section 2.3, are shown in Figure 2. We additionally see that the sensitive range of cWB grows faster with chirp mass than the range of template-based searches, making cWB additionally useful for circular binaries at higher masses (see also Abbott et al. 2017b).

3.2. Astrophysical Constraints

In order to compare our results to astrophysical source populations, we calculated the volume-time (VT) probed by our search. VT depends on the mass distribution of the BBH population. Dynamical formation channels are expected to

result in different BH mass and mass ratio distributions than BBH mergers from field binaries (Kimpson et al. 2016; Rodriguez et al. 2018). We considered a BBH mass distribution such that the mass of the more massive BH, m_1 , follows a power-law distribution $m^{-\beta}$ within the range $[5 M_\odot, 50 M_\odot]$ for different β values (see below), while the second BH's mass, m_2 is uniformly distributed within the range $[5 M_\odot, m_1]$. The mass distribution of BBH mergers detected by Advanced LIGO and Advanced Virgo so far is somewhat different from this assumed distribution (Abbott et al. 2019d, 2019e). However, eccentric BBH merger channels are likely responsible for only a subset of these observations and therefore they do not fully determine the overall spectrum. With this mass distribution model, we find that $VT(\beta) \approx \{6.6, 2.4, 0.75\} \times 10^{-2} \text{ Gpc}^3 \text{ yr}$ for $\beta = \{1, 2, 3\}$, respectively.

The BBH merger rate density for processes that can lead to eccentric orbits in the Advanced LIGO and Advanced Virgo band is mostly predicted to be up to a few $\text{Gpc}^{-3} \text{ yr}^{-1}$ (Kocsis et al. 2006; Antonini & Rasio 2016; Rodriguez et al. 2016b; Bartos et al. 2017; Petrovich & Antonini 2017; Silsbee & Tremaine 2017; Hamers et al. 2018; Hoang et al. 2018; Yang et al. 2019), while some more extreme models predict merger rate densities up to $100 \text{ Gpc}^{-3} \text{ yr}^{-1}$ (Rasskazov & Kocsis 2019; VanLandingham et al. 2016). The fraction of mergers from these processes that have high eccentricity ($e \gtrsim 0.1$) ranges from $\sim 1\%$ (Randall & Xianyu 2018a, 2018b) to close to all mergers (Petrovich & Antonini 2017; Gondán et al. 2018).

In order to understand the astrophysical rate density constraints of our results, we considered a dynamical formation channel that produces BBH mergers at rate density R_{dyn} , with a mass power-law index β (see above). We assumed that a fraction f_{ecc} of mergers from this channel have eccentricities $e > 0.1$, and that this BBH sub-population follows the mass distribution considered here. We further assumed that all BBH mergers detected by Advanced LIGO and Advanced Virgo so far have eccentricities $e < 0.1$. The expected number of eccentric mergers ($e > 0.1$) from this model detected by cWB during O1 and O2 is then

$$\langle N_{\text{cWB,ecc}} \rangle = R_{\text{dyn}} f_{\text{ecc}} VT(\beta). \quad (1)$$

Given that no such eccentric merger was detected, the Neyman 90% confidence-level upper limit is

$$R_{\text{ul,ecc}} = \frac{2.3}{f_{\text{ecc}} VT(\beta)} \quad (2)$$

where $\beta = \{1, 2, 3\}$. We obtained

$$R_{\text{ul,ecc}} = \{30, 90, 300\} f_{\text{ecc}}^{-1} \text{ Gpc}^{-3} \text{ yr}^{-1} \quad (3)$$

for $\beta = \{1, 2, 3\}$, respectively. The quoted approximate values were rounded to the first significant digit. We found that this result does not depend on the eccentricity distribution of the source population, as our search sensitivity only weakly depends on eccentricity.

Our results rule out models predicting $\gtrsim 100 \text{ Gpc}^{-3} \text{ yr}^{-1}$ merger rate densities (VanLandingham et al. 2016; Rasskazov & Kocsis 2019) for $\beta \lesssim 2$ if the majority of mergers in the given model have eccentricities $e > 0.1$, while the results are consistent with a number of other models (e.g., Antonini & Perets 2012; Antonini et al. 2017; Fragione et al. 2019b).

4. Conclusion

We searched for eccentric BBH mergers using the cWB algorithm. We showed that the sensitivity of our method is independent of the eccentricity at the time the binary enters Advanced LIGO and Advanced Virgo's frequency band at $\sim 10 \text{ Hz}$.

Our search only uncovered binaries that have also been found by template-based searches that do not appear to have eccentric orbits. We interpreted this non-detection in light of the expected merger rate density of BBH formation channels that can produce eccentric orbits, and the fraction of these mergers that have eccentricities $\gtrsim 0.1$. Our results rule out the highest end of the rate density predictions ($\gtrsim 100 \text{ Gpc}^{-3} \text{ yr}^{-1}$) assuming that the majority of the binaries from these channels have $e > 0.1$, and that the power-law index of the BH mass spectrum is $\lesssim 2$.

Future observing runs by Advanced LIGO, Advanced Virgo and KAGRA (Aso et al. 2013) will provide substantially improved sensitivity to probe formation mechanisms resulting in eccentric binaries (Abbott et al. 2018).

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